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MATERIALS FOR ADVANCED TURBINE ENGINES

Project Completion Report
Project 3

ADVANCED BLADE TIP SEAL SYSTEM
Volume II

By

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16. Abstract

This report presents the results of the endurance and performance engine tests conducted on monocrystal/abrasive-tipped CF6-50 Stage 1 HPT blades fabricated in Task VII of MATE Project 3. Two engine tests were conducted. The endurance engine test was conducted for 1000 "C" cycles. The performance engine was conducted on a variable cycle core engine.

Posttest evaluation and analyses of the blades and shrouds included visual, dimensional, and destructive evaluations.

The results reported represent work performed on Tasks VIII and IX of MATE Project 3 and are presented as FEDD Category 2 data. Work performed on Tasks I through VII of Project 3 is presented in Volume I.

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1.0 SUMMARY

The goal this project was to demonstrate the increased efficiency and increased blade life attainable through the use of an advanced turbine blade-tip-seal system. The turbine blade tip design consisted of an environmentally resistant activated diffusion bonded monocrystal superalloy combined with a thin layer of aluminum oxide abrasive particles entrapped in an electroplated NiCr matrix. The project established the tip design and joint location, characterized the monocrystal tip alloy and abrasive tip treatment, and established the manufacturing and quality control plans required to fully process the blades. Approximately 150 blades were finished machined and 100 were made available for endurance and performance test engines.

Two engine tests were conducted. The first engine test evaluated 20 advanced tip blades through cyclic endurance testing on a CF6-50 fan engine. The second test evaluated a full set (80) of advanced tip blades on a variable-cycle CF6-50 performance core engine. Both engines completed their required cycles with no major problems. During the engine tests, periodic borescope inspectious were conducted to assess the condition of the blades and shrouds. The engine tests were followed by posttest analyses including visual, dimensional, and destructive evaluations on selected blades and shrouds.

The endurance engine test was run for 1000 simulated flight cycles ("C" cycles) and was conducted on CF6-50 fan Engine 455-509/14. The engine test results showed that the monocrystal tip material and ADB joint were able to withstand the rigors of cyclic engine testing (which included a heavy rub). However, the oxidation resistance and thermal fatigue resistance of the monocrystal tip material were not sufficient to achieve the 2X life goal over conventionally cast René 80.

The performance testing, which was conducted on CF6-50 core Engine 455-511/4, resulted in a successful demonstration of the abrasive tip system. A heavy rub occurred over six CoNiCrAlY shrouds (~90°) and resulted in shroud removal of up to 0.46 mm (0.018 inch) which exceeded the 0.3 mm (0.013 inch) program goal.

2.0 INTRODUCTION

The primary objective of the Materials for Advanced Turbine Engines (MATE) Project is the introduction of new materials technologies into advanced aircraft turbine engines to achieve potential economic and operational performance advantages. The program encompasses accelerated transfer of selected material technologies by scaling them up from the laboratory-feasibility stage to engine demonstration as well as performing cost/benefit analyses to provide guidance in the selection of the candidate material technologies to be scaled up.

Project 3, the subject of this technical report, demonstrated the payoff of an advanced tip-seal system designed to maintain close tolerances between turbine blade tips and turbine shrouds and, at the same time, be resistant to environmental effects including high-temperature oxidation, hot corrosion, and thermal cycling. The project was structured toward the successful engine demonstration of an improved efficiency, long life, tip seal system for turbine blades; the technical effort was divided into the nine principal tasks listed below:

- Task I - Turbine Blade Tip Seal System Design
- Task II - Monocrystal Tip Alloy Evaluation
- Task III - Abrasive Tip Evaluation
- Task IV - Seal System Verification
- Task V - Quality Control Plan
- Task VI - Manufacturing Process Plan
- Task VII - Seal System Manufacture and Component Test
- Task VIII - Engine Tests
- Task IX - Posttest Analysis

The goal of the project was to demonstrate the increased efficiency and increased blade life attainable through the advanced blade-tip-seal system. The turbine blade tip consisted of a bonded, environmentally resistant, activated diffusion bonded (ADB) monocrystal superalloy covered with a thin layer of aluminum oxide abrasive particles entrapped in an electroplated NiCr matrix. The project established the tip design and joint location, characterized the monocrystal tip alloy and abrasive tip treatment, and established the manufacturing and quality control plans, and fully manufactured over 150 blades for component and engine testing. The results reported herein represent work performed in Tasks VIII and IX of MATE Project 3 and are presented as FEDD Category 2 data.

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3.0 ENGINE TEST PROGRAM

Two separate CF6-50 engine tests, one endurance and one performance, were conducted to demonstrate the life and clearance improvement through the use of the advanced turbine blade tip system. While both tests evaluated the identical blade tip treatment, different HPT shroud materials were used in each test. The endurance engine test evaluated 20 (1/4 set) advanced tip blades and was assembled with Bradelloy* shrouds whereas the performance engine test evaluated 80 advanced tip blades (a full set) and utilized vacuum plasma sprayed CoNiCrAlY shrouds.

3.1 PREPARATION FOR ENGINE TEST

The blades for each CF6-50 engine test were manufactured as described in Tasks VI and VII of the MATE 3, Volume I report. Twenty blades were assembled into CF6-50 endurance fan Engine 455-508/21 and 80 blades were assembled into CF6-50 performance core Engine 455-511. The blades were manufactured to the quality control constraints required by CF6-50 Design Engineering for factory engine test blades.

3.2 VERIFICATION

In Volume I of the MATE 3 final report, mechanical, physical, and component testing of the advanced tip seal system is discussed extensively. Exhaustive testing was conducted on the monocrystal/abrasive tip system to assure reliability prior to engine test evaluation. The results of the mechanical property and component testing showed that the materials and processes required to fabricate the blades were sufficient for safe engine operation.

3.3 ENGINE TESTING

3.3.1 Endurance Testing

Twenty advanced tip CF6-50 high pressure turbine blades were assembled into Engine 455-508/21 and were engine tested for 1000 standard "C" cycles. In a test cell, "C" cycle engine testing simulates the temperature, stress, and cyclic nature of actual engine operation on a commercial transport aircraft and is shown graphically in Figure 1. A typical "C" cycle includes ground idle, takeoff, climb, cruise, descent, and thrust reverse engine operating conditions.

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*Bradelloy, the current HPT shroud material for the CF6-50 is comprised of sintered NiAl and will not sufficiently abrade with the Al_2O_3 abrasive tip system (see Task III wear test results in Volume 1).

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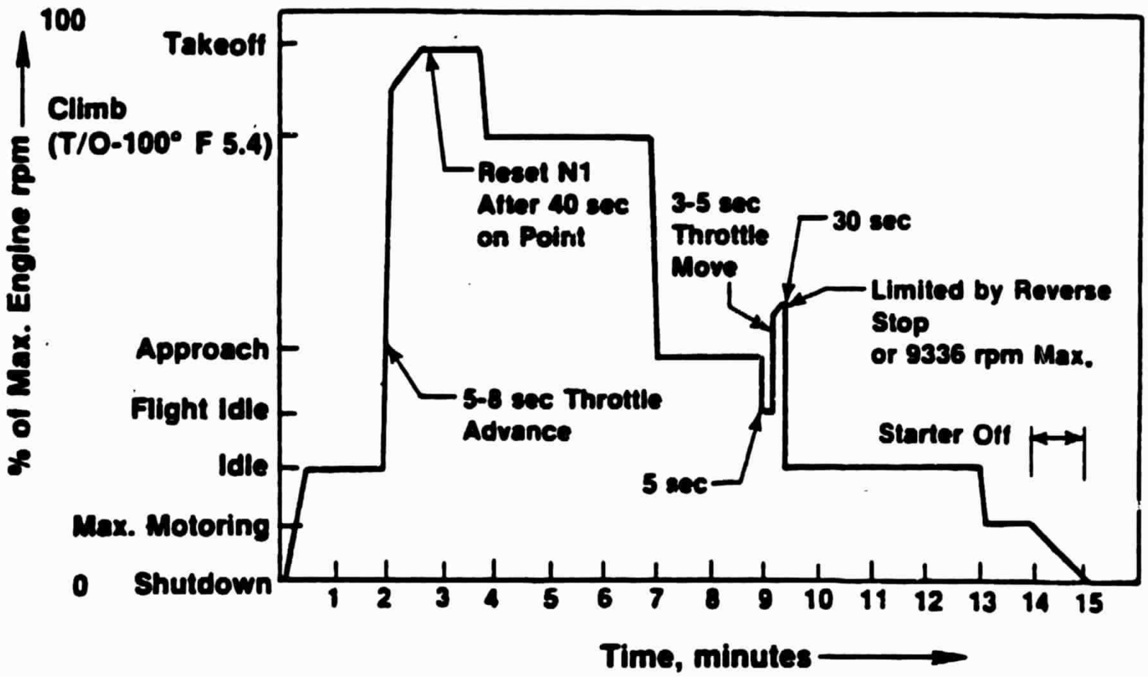

Figure 1. CF6-50 Simulated Service "C" Cycle.

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3.3.1.1 Engine Test Plan

The engine chosen to evaluate the benefits of the advanced tip system was factory endurance Engine 455-508/21 which was scheduled to run 1000 "C" cycles and attain a maximum exhaust gas temperature (EGT) of 1778° F. Table I shows variations in the type of "C" cycles run, the number of "C" cycles for each variation, and the corresponding exhaust gas temperatures for each cycle.

Table I. Engine "C" Cycle Mix For Test Engine 455-511/21.

Type of "C" Cycles	Exhaust Gas Temperature	Number of Cycles
M	Below 890° C (1634° F)	150
N	891°-925° C (1635°-1697° F)	350
O	926°-950° C (1698°-1742° F)	300
P	951°-960° C (1742°-1760° F)	100
P1	961°-965° C (1761°-1769° F)	50
P2	966°-970° C (1770°-1778° F)	50

Twenty advanced tip blades were installed along with 16 current production, conventionally cast René 80 blades of the identical cooling configuration. The balance of the blades were comprised of René 150 blades (from MATE Project 2) and conventionally cast René 80 blades with advanced cooling configurations. All of the blades in the rotor were tip ground to the same rotor dimension. The monocrystal-tipped blades which were abrasive-treated were therefore 0.13 to 0.15 mm (0.005 to 0.006 inch) longer than the balance of the blades in the rotor. The turbine shrouds were current-production Bradelloy and were ground to produce a severe intentional tip rub at the 3:00 position to simulate the worst possible conditions that a blade tip might experience under actual break-in or flight conditions. The severe intentional tip rub was designed to assess the ability of the tip-to-blade ADB joint to withstand abnormally high rub-induced stresses.

Engine 455-508/21 was run for 1000 "C" cycles (250 hours) without any major interruptions. Throughout the test, periodic borescope inspections were conducted to assess the condition of the blade tips. The borescope inspections indicated that an early rub had occurred and the abrasive was completely removed after initial break-in (~4 hours). No distress was noted in either the monocrystal tip material or at the ADB joint throughout the test duration. Using the borescope inspection, it was not possible to assess whether or not shroud material had been removed by the abrasive tipped blades.

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3.3.2 Performance Testing

Since engine efficiency is strongly related to HPT blade tip-to-shroud clearances, compensation for shroud distortions and rotor shift are made by offset grinding of the shroud assembly at engine build. However, varying operating conditions add additional turbine distortions that cannot be predicted. Abrasive tip turbine blades offer the potential to "grind" the shroud round, in-situ, and remove the unpredictable shroud distortions.

The objective of the performance engine test was to establish the capability of the abrasive tip system to remove shroud material in an actual engine environment. The engine test was conducted so that a sufficient incursion would occur that would completely remove the abrasive tip, thus providing the design engineers with data on the maximum capability of the system. This data could then be used to establish the precise shroud offset grind configuration and build clearances that would provide the maximum benefit of the abrasive tip system for production CF6-50 engines.

3.3.2.1 Engine Test Plan

A full set (80) of the advanced tip (monocrystal Normalloy + Al_2O_3 abrasive) HPT blades and a full set of VPS CoNiCrAlY solid shrouds were installed in CF6-50 core Engine 455-511/4. The shrouds were ground to create an interference of 0.6 mm (0.024 inch) at the 3:00 position where it could be viewed by borescope inspection.

Unlike the "C" cycle testing conducted on the endurance test, the performance test involved various types of cycles including slow acceleration/deceleration, steady-state running, and chops and bursts, and was designed to evaluate various other engine design modifications as well as the abrasive tip system. The performance engine test ran for a total of approximately 27 hours.

Periodic borescope inspections were conducted throughout the duration of the test to assess blade tip and shroud wear. The first borescope inspection, at 2-1/2 hours, showed that a rub had occurred; however, shroud loss and blade tip condition could not be accurately assessed. Subsequent borescope inspections were conducted mainly to monitor the blades and shrouds for radical changes (deterioration) that might occur. No major changes in the condition of either the blade tips or shrouds were noted throughout the engine test.

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4.0 POSTTEST ANALYSES

4.1 ENDURANCE TEST RESULTS

4.1.1 Post Teardown Visual Inspection

As mentioned earlier, the engine experienced a severe rub during break-in and, as anticipated, removed all of the abrasive. The actual magnitude of the rub could not be assessed because of deterioration of the shrouds which had occurred during cyclic testing. Visual inspection of the blade tips showed that 11 of the 20 monocrystal tipped blades exhibited radial cracking, as shown in Figure 2. Only 3 of the 16 identically cooled, conventionally cast René 80 blades showed radial tip cracks. Moderate surface oxidation was noted on both the monocrystal tipped blades and the CC René 80 blades. No distress at the monocrystal-to-blade ADB joints was observed on any of the blades.

4.1.2 Metallurgical Investigation

Five of the 20 monocrystal-tipped turbine blades from Engine 4[illegible]5-508/21 were submitted for metallurgical evaluation. Four of the blades had radial tip cracks; the fifth blade exhibited a dent (FOD) on the convex side of the blade at midchord. The purpose of this evaluation was to assess the condition of the monocrystal tip material and the bond joint and to determine the origin and cause of the radial cracking that had occurred in the monocrystal material.

All exposed (uncoated or cracked) surfaces of the monocrystal Normalloy material exhibited internal oxidation ranging from moderate to high (as shown in Figures 3 and 4). Oxide penetration in the cracks was severe, suggesting that the cracks had initiated relatively early in the engine test, probably as the result of thermal fatigue. The cracks appeared to be low cycle fatigue in mode and initiated in the oxidized layer of the monocrystal and extended down through the bond joint and into the René 80 blade material as shown in Figure 5. The balance of the monocrystal material exhibited a complete "twinning" type of recrystallization (Figure 6), which conceivably could have been caused by the severe rub encountered during the early portion of the engine test. In all cases, the monocrystal-to-blade ADB joint was intact with no distress noted. The dent (FOD of unknown origin) on the one blade, shown in Figures 7 and 8, was confined to only the monocrystal material where conventional recrystallization was evidenced; again, "no" distress was found in the ADB joint.

4.1.3 Endurance Engine Test Conclusions

The method used to join the monocrystal Normalloy to the conventionally cast blade (that is, activated diffusion bonding) was shown to be a reliable

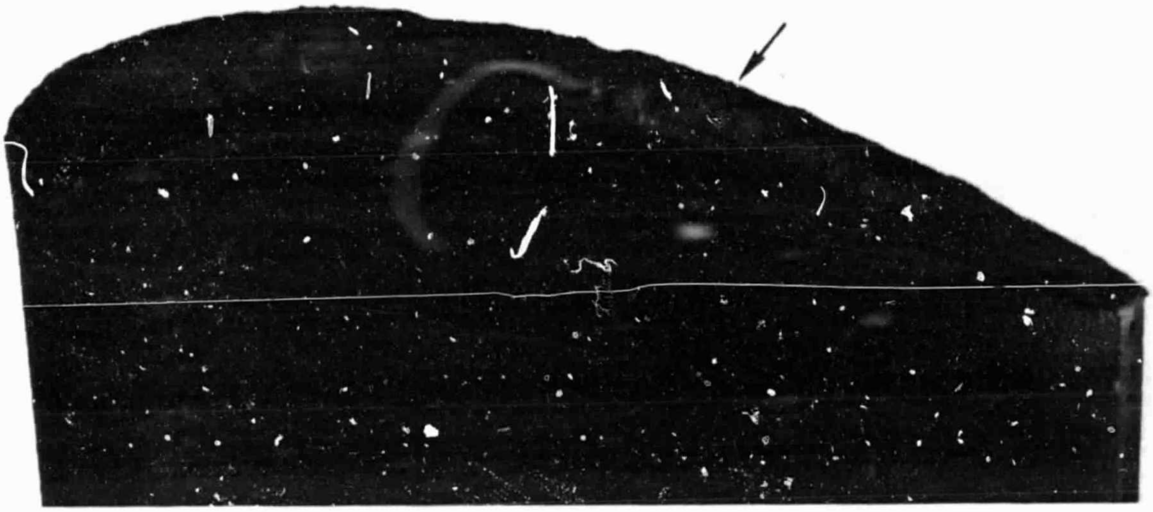

Figure 2. MATE Project 3 Blade Tip After Endurance Testing (Note Tip Crack).

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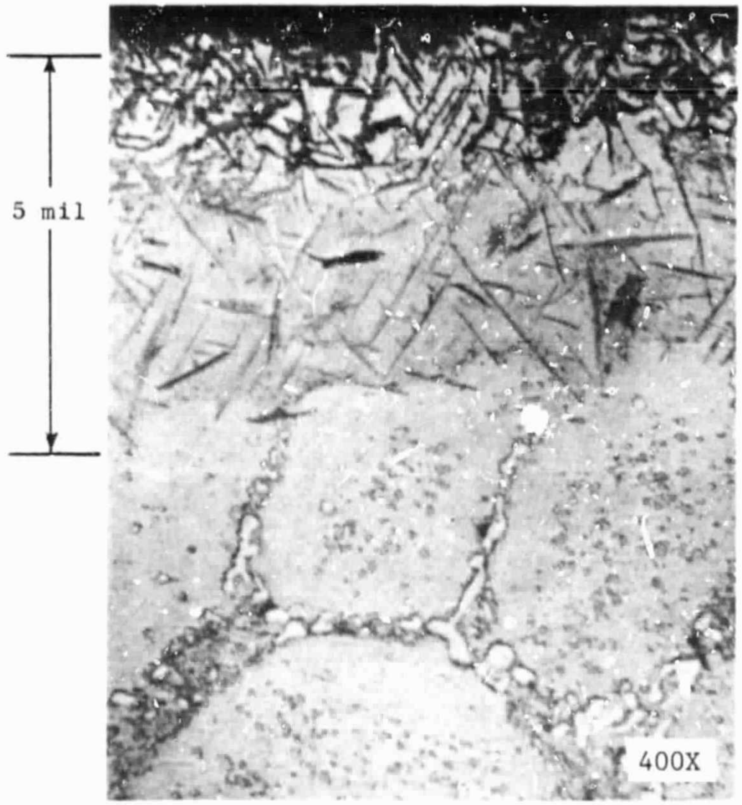

Figure 3. Monocrystal Normalloy Tip After Endurance Testing Showing Oxidized Layer.

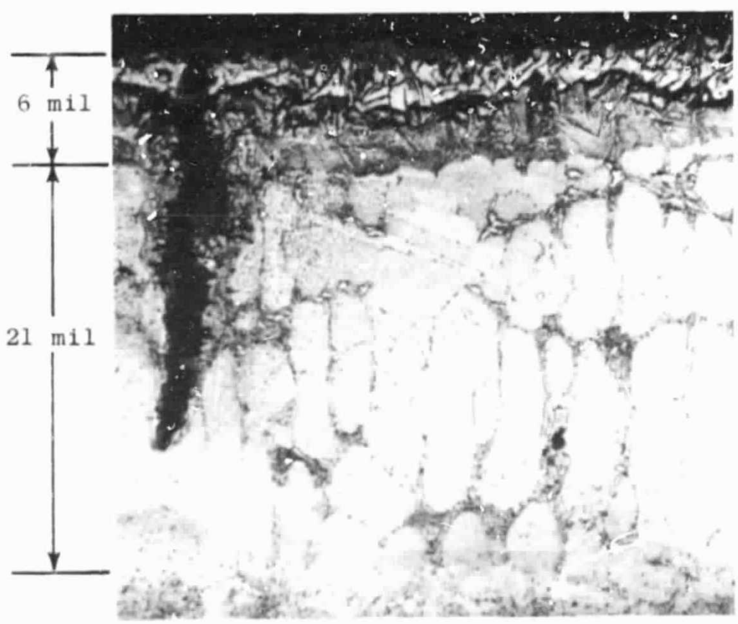

Figure 4. Radial Crack in Monocrystal Normalloy Tip After Endurance Testing.

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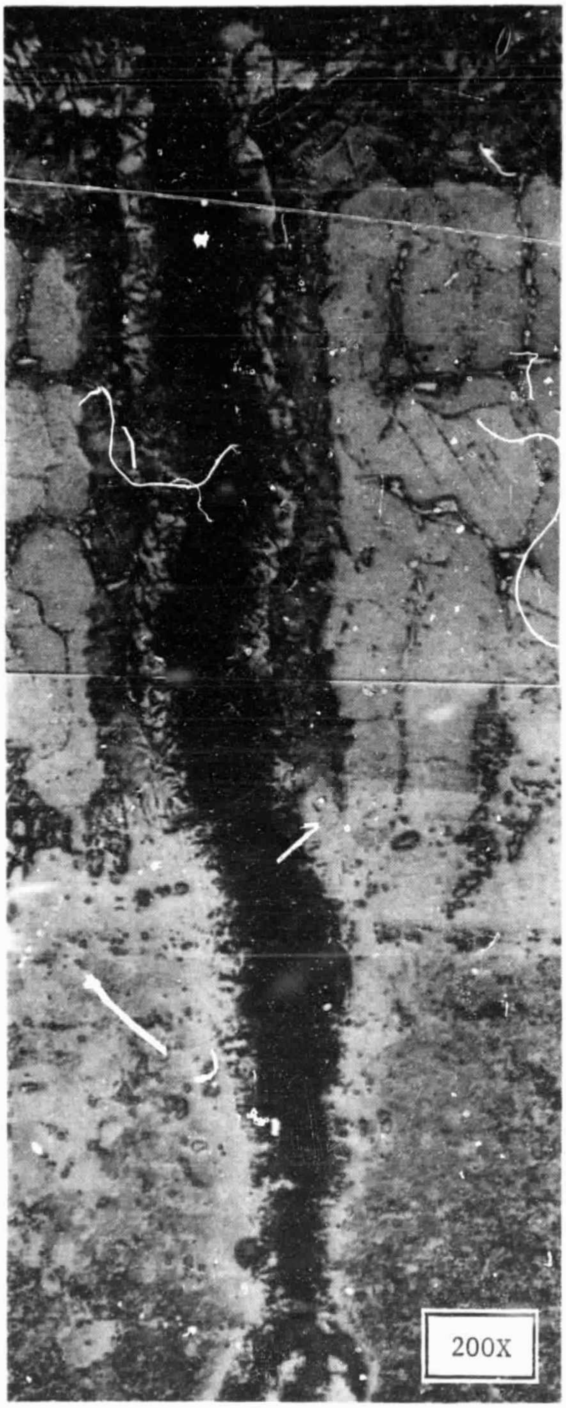

Figure 5. Crack in Monocrystal Normalloy Blade Tip After Endurance Testing. The Crack Extended Through the ADB Joint and Into the René 80.

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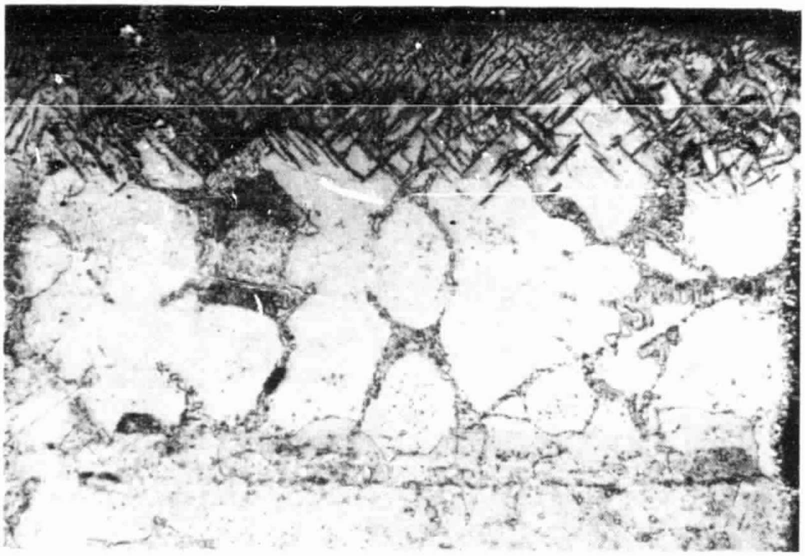
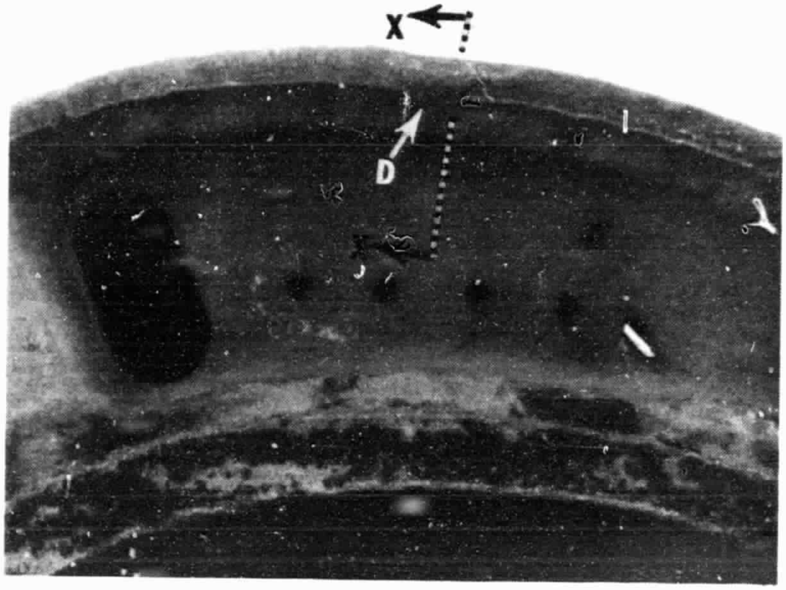


(Concave Side) 100X

Figure 6. Monocrystal Normalloy Tip Material After Endurance Testing Showing Recrystallization.



8X

Figure 7. Dent (FOD) in Blade Tip After Endurance Testing.

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(Unetched) 50X

Figure 8. Cross Section of Dent in Monocrystal Normalloy Blade Tip.

process and was sufficiently strong to withstand a severe tip/shroud incursion. The monocrystal Normalloy tip material, however, did not demonstrate the oxidation and LCF resistance that was projected as the result of the laboratory and rig testing conducted in Tasks II, IV, and VII. Further investigation into the cause of the cracking revealed that the coefficient of thermal expansion of the Normalloy, which was greater than that of René 80, would have produced a high stress in the monocrystal tips during engine cycling. The additional stress-induced strain could have produced the recrystallization and/or thermal fatigue cracking, resulting in the lower life observed. The abrasive tip was totally removed and, as expected, did not sufficiently abrade the Bradelloy shroud material. The Bradelloy shroud material was oxidized and was swelled slightly and, in the region of this rub, exhibited metal transfer (scabbing) of the tip material.

4.2 PERFORMANCE TEST RESULTS

4.2.1 Visual/Dimensional Inspection

The rotor assembly (blades) and shroud assembly after engine testing are shown in Figures 9 and 10. As shown in Figure 10, considerable rub (~180°) had occurred, the heaviest of which occurred on six shrouds between the 1:00 and 4:00 positions (~90°). The shrouds were removed from the shroud assembly and measurements were made to determine the extent of shroud removal. The volume of material removed was substantial. The greatest depth of shroud rub was at a position corresponding to the midchord of the blade where up to 0.46 mm (0.018 inch) of shroud had been removed as shown in Figure 11. Lesser, but still significant (0.30 mm [0.012 inch]), amounts of shroud material were removed at regions corresponding to the ends of the tip cap cavity. The very trailing edge of the tip did not remove any shroud material which was believed to be the result of the higher temperatures present in this uncooled region of the blade tip. A distribution of grind capability versus axial position along the blade tip is shown in Figure 12.

The blades were removed from the rotor and were visually examined. As shown in Figure 13, all of the abrasive treatment on all of the blades was removed at the tip; however, some abrasive still remained on the suction (convex) side of the airfoil. Considerable debris also was present on the blade tips. The monocrystal material and ADB joint appeared unaffected by the engine test.

4.2.2 Metallurgical Evaluation

Selected blade tips and shrouds were sectioned and evaluated. Figure 14 shows a cross section of one of the blades at approximately midchord. As shown in this figure, both the monocrystal material and the ADB joint were intact. Also shown is the debris that had collected on the suction sides of the squealer tips. This debris has been identified as CoNiCrAlY and was shown to be on all of the blade tips. Note also that the abrasive treatment is

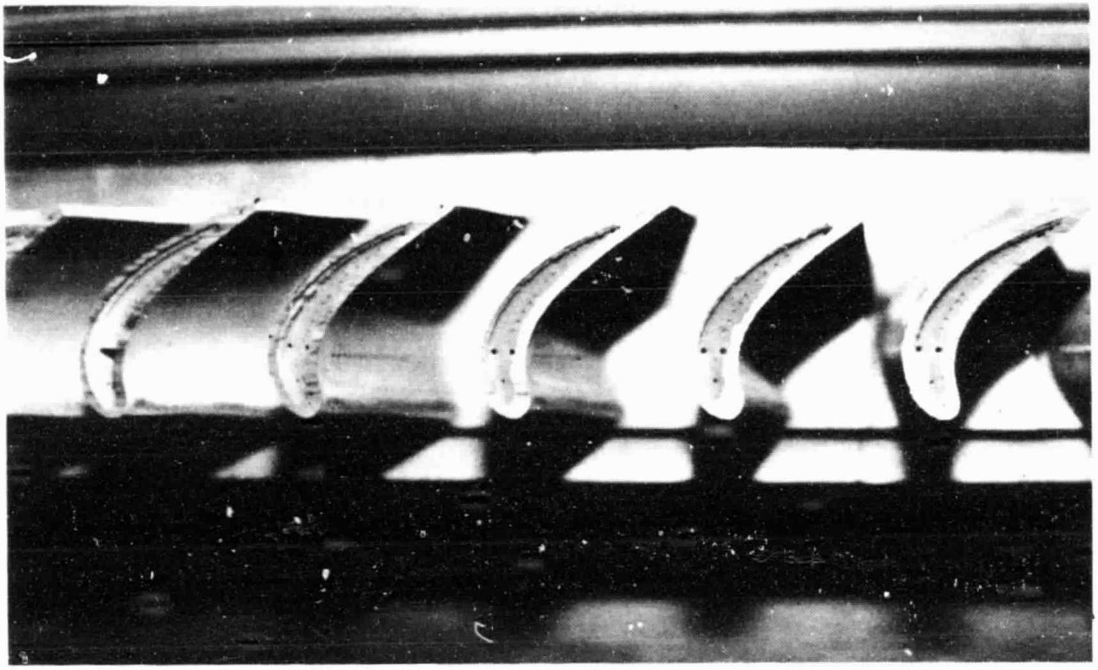

Figure 9. Stage 1 HPT Blades with the Advanced Tip System After Performance Engine Testing.

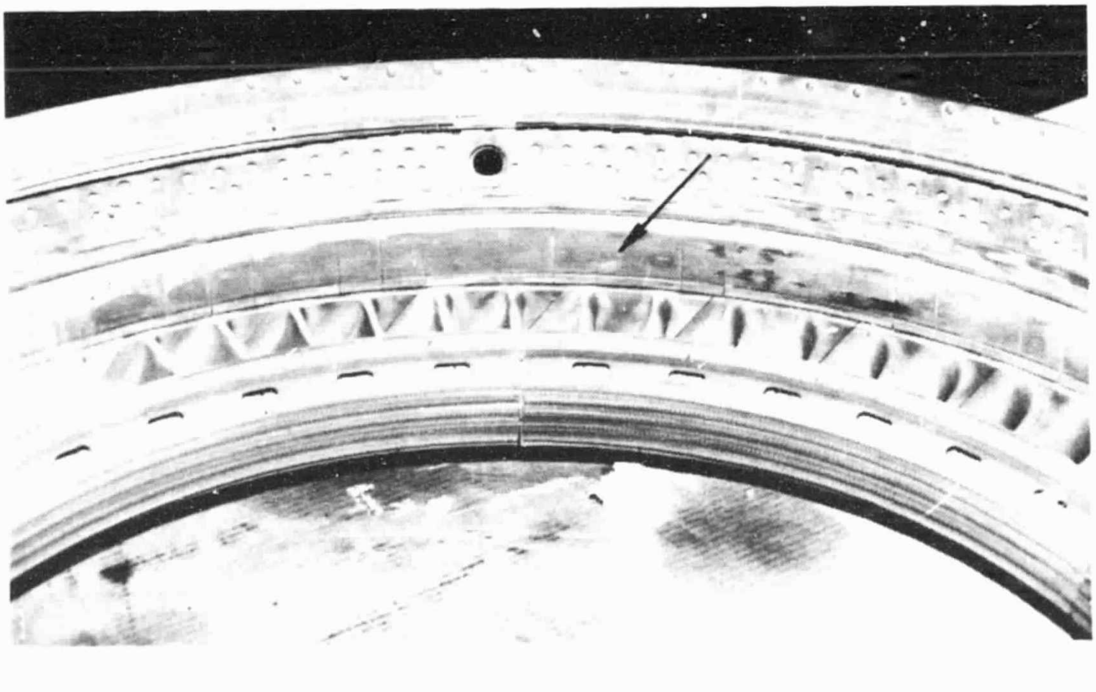

Figure 10. CoNiCrAlY Shrouds After Performance Engine Testing.

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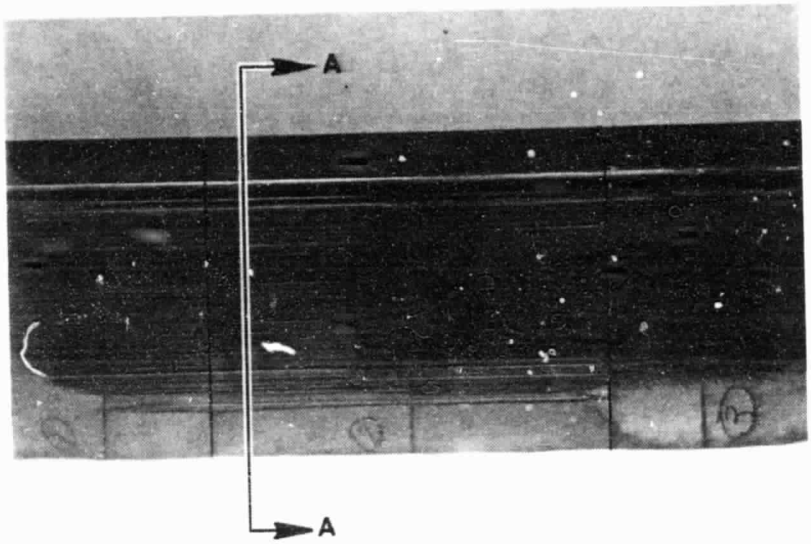

Figure 11. CoNiCrAlY Shroud Segment After Performance Engine Testing Showing Wear Path Generated by the Abrasive Blade Tip (See Figure 15 for Subsection A-A).

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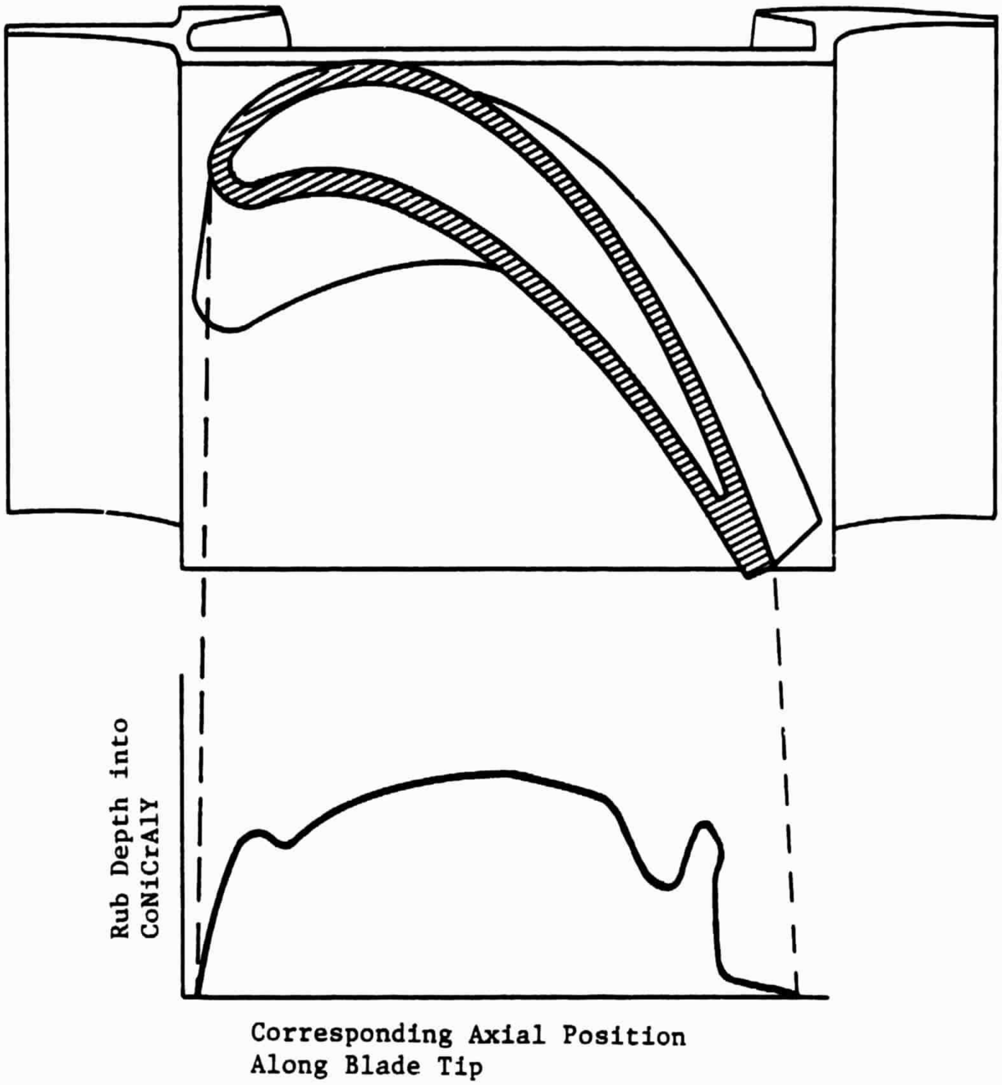

Figure 12. CoNiCrAlY Shroud Removal Versus Axial Position Along Tip After Engine Test.

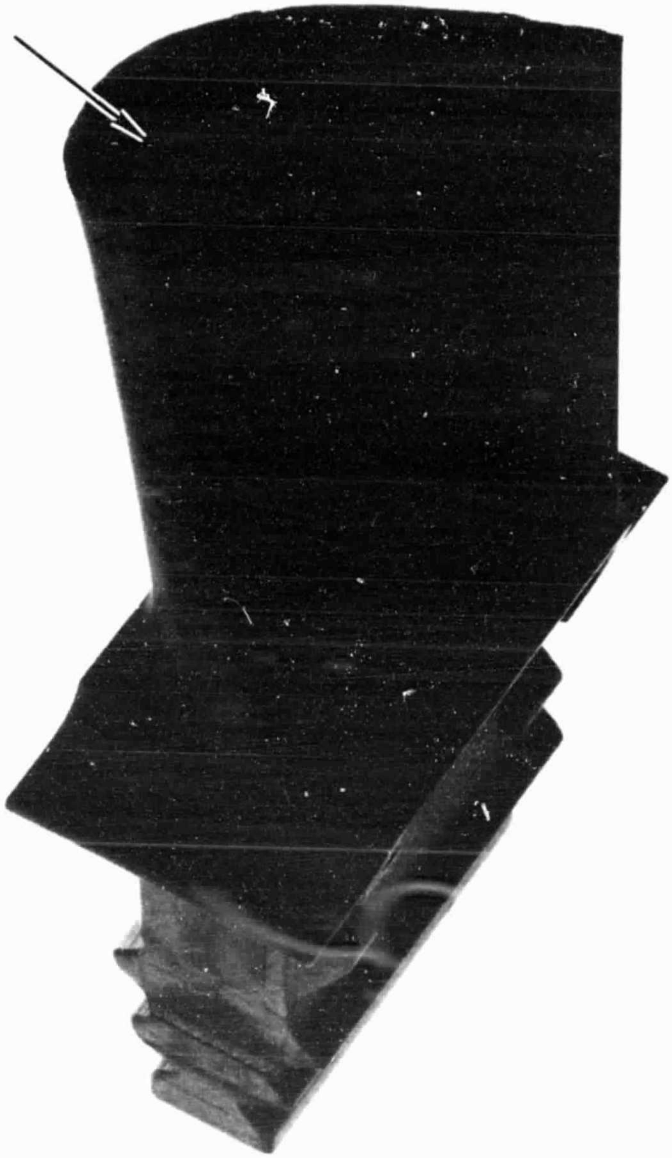

Figure 13. Blade Tip Showing Tip Wear
and Debris.

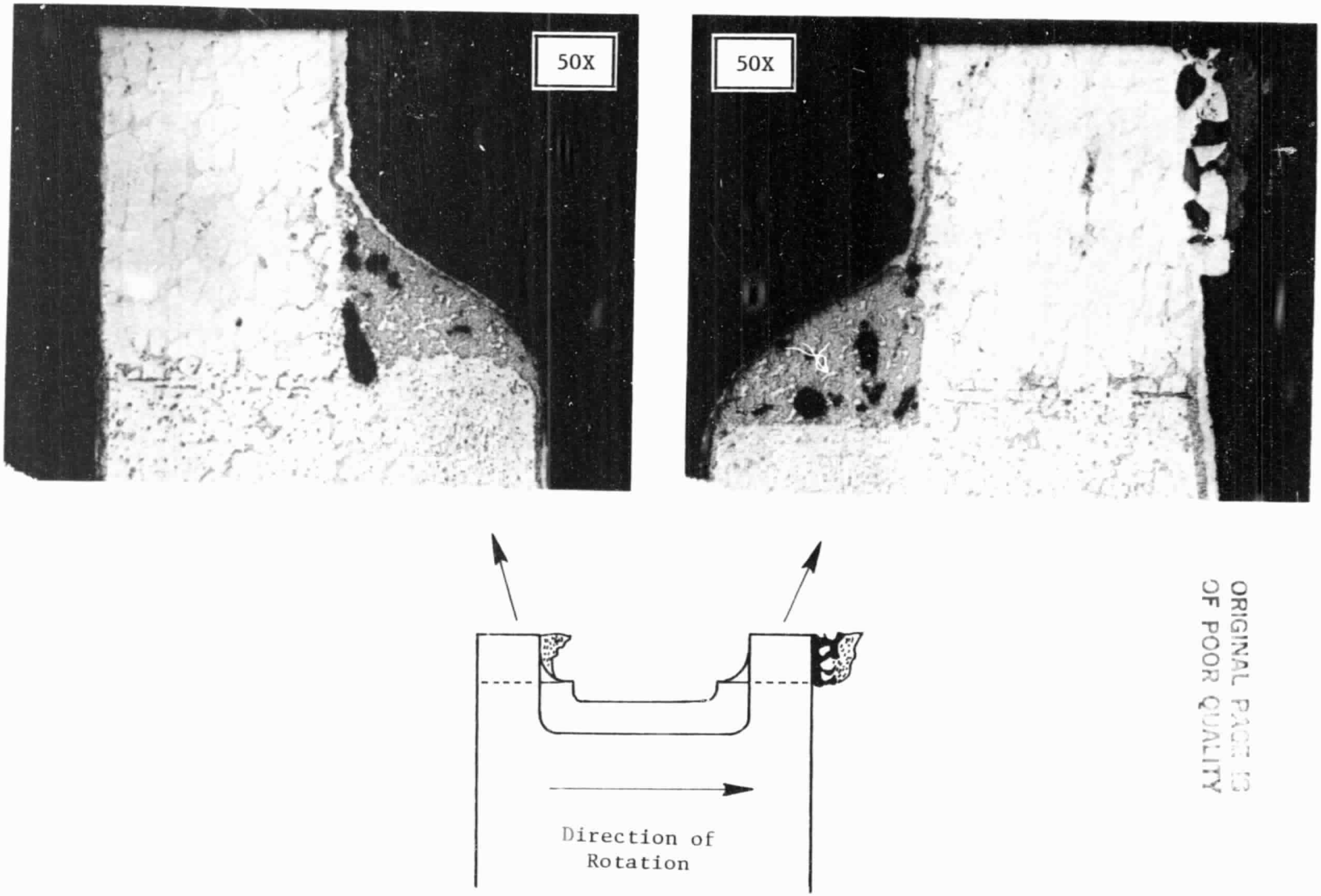

Figure 14. Cross Section of Advanced Blade Tip System After Endurance Engine Testing.

[redacted]

still present on the suction side of the airfoil. The condition shown in Figure 14 was typical of all of the sections evaluated.

Figure 15 shows a cross section of one of the rubbed CoNiCoAlY shroud segments. The structure was typical of VPS CoNiCrAlY and exhibited no unusual phases or deterioration.

4.2.3 Results and Conclusions

Since a core engine and a fan engine differ in their operating conditions, shroud distortion and consequently rub characteristics of each, also differ. A fan engine shroud system will generally distort locally over only a few shrouds whereas a core engine will experience a more "uniform" distortion and will result in a large circumferential rub which was evidenced on Engine 455-511/4. The results of this test were used to predict the effectiveness of the abrasive tip system when used in a fan engine under actual production engine break-in conditions. Figure 16 shows the relationship between grind capability* and grind depth for the abrasive tip system when used with the CoNiCrAlY shroud system and plots the actual data (32.5 in^2) from Engine 455-511/4. This plot depicts four different types of probable shroud distortion ranging from a 0.20 mm (0.008 inch) rub over 12 shrouds to a 0.41 mm (0.016 inch) rub over six shrouds. The flat section in the upper part of the curves represents a total removal of the distortion and a 360° grind. The 0.41 mm (0.016 inch) rub over six shrouds is probably the most realistic in a CF6-50 engine break in.

Engine 455-511/4 experienced a severe, but predicted, rub condition that resulted in considerable shroud removal. As planned, the rub was sufficient to assess the full capability of the abrasive tip treatment. Based on the results of this engine test, the Al_2O_3 abrasive tip system, as used in conjunction with the CoNiCrAlY shroud material, was capable of reducing blade tip-to-shroud clearance loss by a minimum of 0.41 mm (0.016 inch) and realized an estimated 0.76% improvement in specific fuel consumption (sfc). The program goal of 0.43% sfc improvement was therefore exceeded.

*Grind capability refers to the projected circumferential area that the blade tip would "sweep" during a rub and is shown schematically in Figure 17.

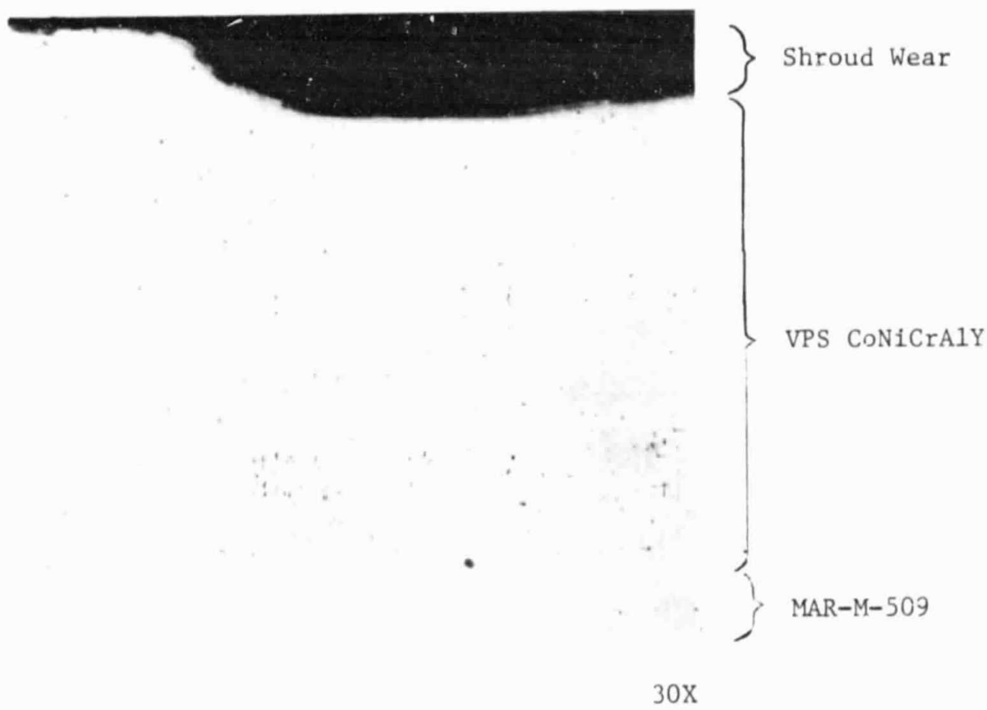

Figure 15. Cross Section of CoNiCrAlY Shroud Segment After Performance Engine Test.

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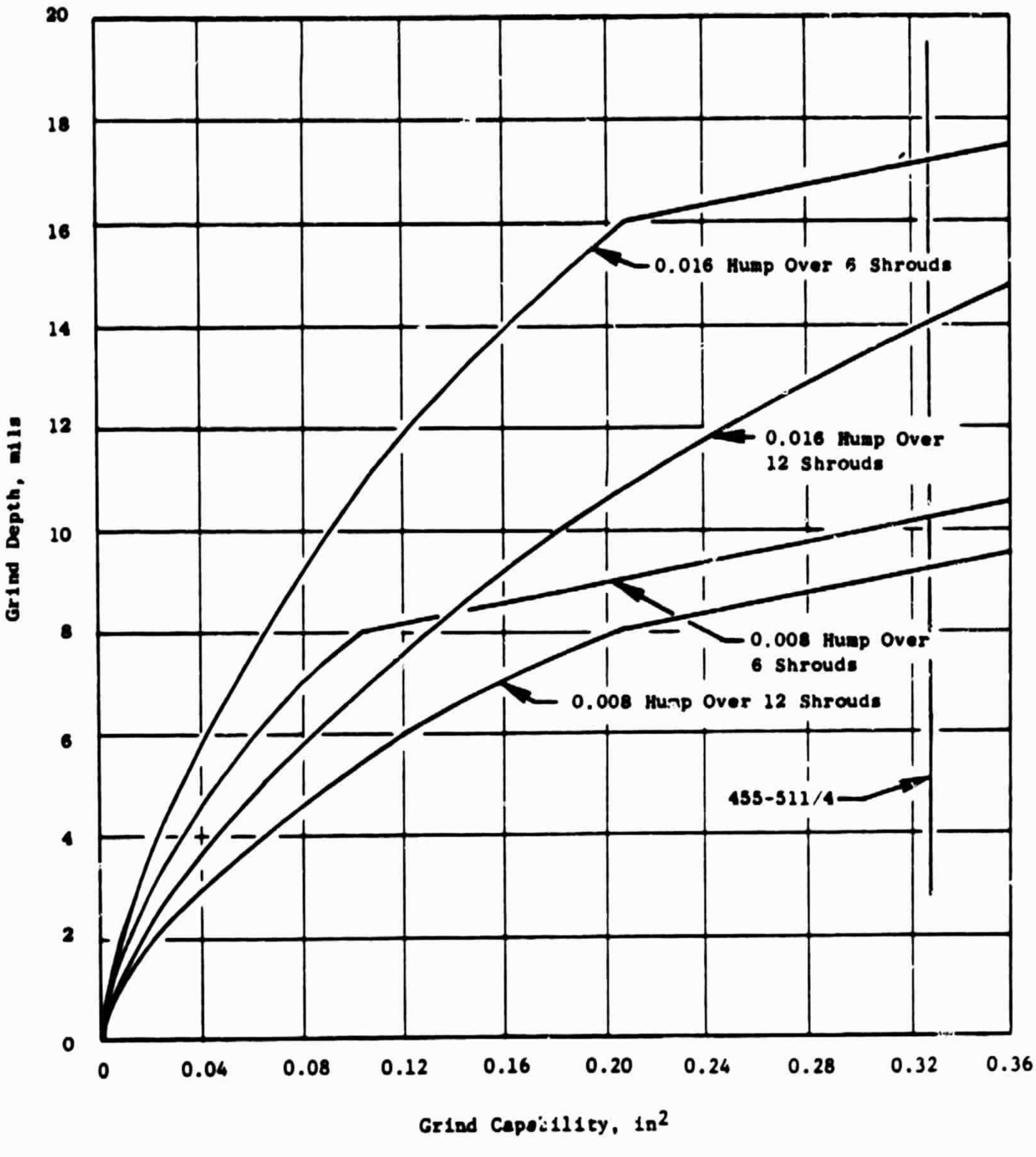

Figure 16. CF6-50 Stage 1 High Pressure Turbine Blades with 100% Abrasive Tips.

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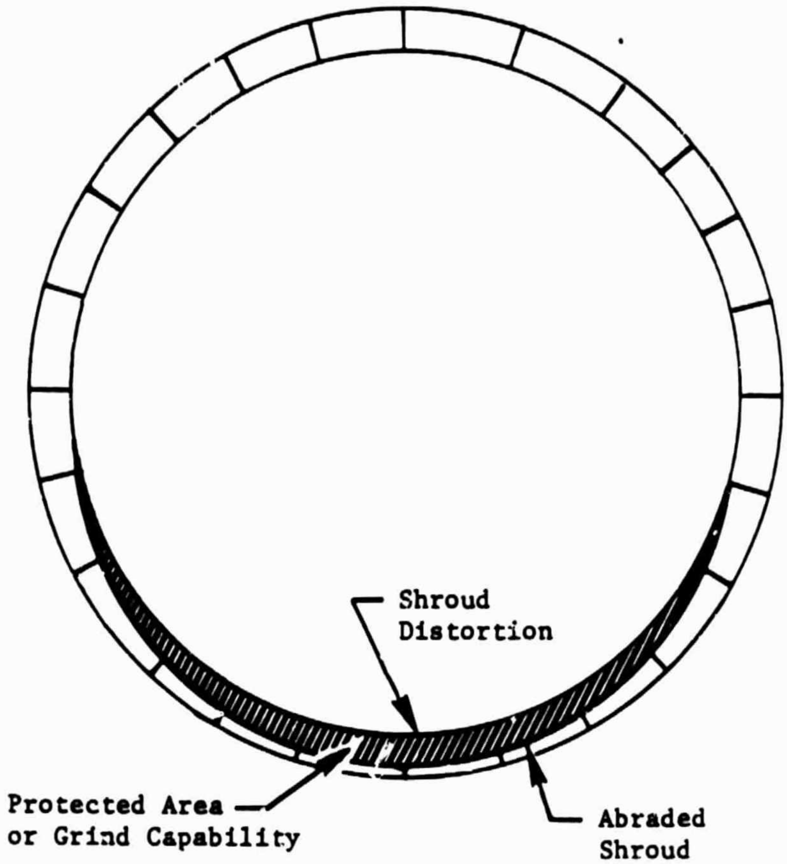

Figure 17. Schematic of Shroud Assembly Showing Grind Capability of Abrasive Tips.

5.0 CONCLUSIONS

The results of the endurance and performance engine tests were mixed. The degree of radial tip cracking encountered in the endurance engine test indicated that the monocrystal Normalloy tip material could not achieve the 2X life goal. The endurance testing did, however, demonstrate the reliability of the activated diffusion bonded joint between the monocrystal tip and the blade to withstand both a heavy rub and shear stresses that were present as the result of the differences in thermal expansion of the René 80 and Normalloy. Improved environmentally resistant tip alloys are currently being evaluated.

The performance test results were extremely encouraging. The abrasive tip system exhibited the capability of removing substantial amounts of CoNiCrAlY shroud material. Analyses of the results indicate that the abrasive tip system, when used in conjunction with the VPS CoNiCrAlY shroud system has the capability to remove typical CF6-50 shroud distortion during engine break in.